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Measurement of Effective Stress Intensity Factor Range of Mode II Fatigue Crack Propagation

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Abstract

Many rolling contact fatigue failures, such as those that occur in railway rails, rolling bearings and gears, is due to the high repeated shear load. In order to prevent such fatigue a failure, the resistance of the material against such a load must be determined. The fatigue crack growth rate is dependent on the stress intensity factor range of the Mode II ΔK_{II}. However, the Mode II crack propagation characteristic varies according to different experiment methods. Therefore, in this study, we measured the effective stress intensity factor range of the Mode II ΔK_{IIeff}. As it is difficult to carry out the Mode II fatigue crack propagation in the laboratory, this test was carried out using a bending load in this study. This bending load was applied to the tips of a double cantilever specimen and the Mode II fatigue crack propagation could be carried out between the two cantilevers. Furthermore, in order to measure the ΔK_{IIeff}, several strain gauges were applied to the specimen around the crack tip. Using this technique, some ΔK_{IIeff} value during the Mode II fatigue crack propagation tests will be reported.

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Keywords: Mode II fatigue crack; Effective stress intensity factor range; compact specimen.

1. Introduction

Mechanical failures such as spalling and pitting will happen in rails, rollers or other components made of metal under heavy repeated contact loading. In order to prevent such type of failures, it is necessary to determine the resistance of certain materials against this type of failure. The crack under repeated contact

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loading, which is considered to lead to the failure, propagates in Mode II. Therefore, the resistance against the propagation could be evaluated by the Mode II fatigue threshold stress intensity factor range, ΔK_{IIth}.

The methods for experiments of the Mode I fatigue crack propagation have already been established [1]. However, for the Mode II fatigue crack propagation, systematic research is limited because this type of crack propagation is difficult to be carried out in the laboratory and there is no standard for these experiments. Early systematic research was done by Otsuka et al. [2]. However, the method they developed could only be applied to soft metals. After this study, Murakami et al. [3] developed an experimental method which could also be applied to hard metals. Later, Otsuka et al. [4] improved their method so it could also be applied to hard metals. However, the results obtained by the two methods using the same material were different. It seems that the interference of the crack faces affects the result. The study done by Matsunaga et al. [5] on the shear mode threshold proved the influence of such interference. Therefore, it is necessary to take the friction on the crack faces into account and determine the Mode II effective stress intensity factor, K_{IIeff}.

During the early experimental effort on K_{IIeff} done by Smith and Smith [6], a set of lines was scribed perpendicular to the precrack and plastic replicas taken at different load intervals during the Mode II cycle. The crack face displacements were measured on the positive replicas using a scanning electron microscope. The authors developed special anvils in order to put a clip gauge on the sides of the specimens straddling the crack to record the displacement over a cycle. K_{IIeff} could then be derived from the load-displacement curve. After this, several teams tried to derived K_{IIeff} in similar ways. The displacement profile of the crack faces were measured on replicas [7], or directly by techniques such as speckle interferometry [8] or clip gauge [9]. Bertolino and Doquet [10] measured the displacement profile using a high resolution digital camera at regular intervals. K_{IIeff} was then derived from the opening and sliding displacement ranges based on a modified asymptotic expression for the Mode I and the force-slide loop, assuming that the friction on the crack faces is uniform. However, it is noted that debris is a product of the abrasion process during the crack propagation and it produces friction on the crack faces that is not uniform. In this paper, a new method assuming that the friction is not uniform was proposed.

2. Experimental Procedures

2.1 Material

The experiments were carried out using commercial grade Japanese Industrial Standards SS400 steel. The chemical composition is shown in Table 1.

Table 1. Chemical composition of specimen

Chemical composition	Ratio in mass%
C	0.11
Si	0.27
Mn	0.55
P	0.021
S	0.023
Fe	bal.

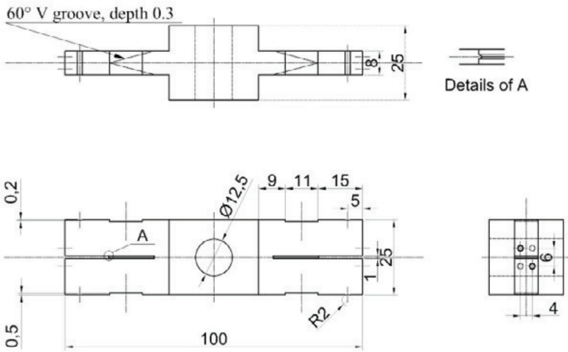

Fig. 1 Shape and dimensions of Specimen;

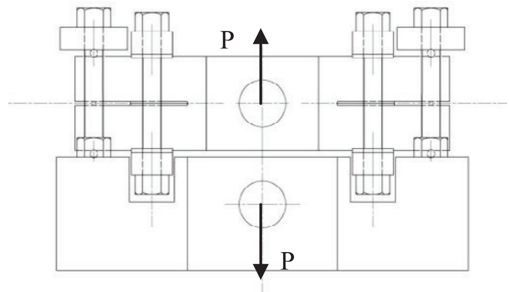

Fig. 2 Setup of the test

2.2 Specimen

Fig. 1 shows the shapes and the dimensions of the specimen. The specimen has a chevron notch and side grooves. The fatigue crack initiates at the tip of the chevron notch shown in the Fig. 1 details of part A. The 60° V-shape groove on the side of the chevron notch causes Mode II fatigue crack growth in the section of maximum shear stress and prevents the crack branching in the direction of the maximum tensile stress which is the Mode I crack. The specimen is more compact and the jig is simpler compared to the one developed by Murakami et al. [3]. Moreover, two crack propagations could be carried out on one specimen at a time, and compressive force was applied on the crack face to avoid crack branching to Mode I [3].

2.3 Experimental Methods

As shown in Fig. 2, the specimen is fixed on the jig. Six ceramic cylinders were placed between the cantilever and jig and between the cantilevers on both sides. As a result, the load applied to the specimen could be divided into two equal sections on the cantilevers. A fully-reversed cyclic tensile load P was applied to the holes of the jig and specimen through two pins by a servo-hydraulic fatigue testing machine at a frequency of 6Hz. In order to suppress the tendency for the Mode I crack branching, vertical compressive force S was applied to the crack faces.

As shown in Fig. 3, six strain gauges divided into two groups, three in each of the different directions, are placed on the two side surfaces of the specimen, that straddling the crack. The elastic strain was derived from the load-strain curve over a cycle, and the friction on that point was deduced.

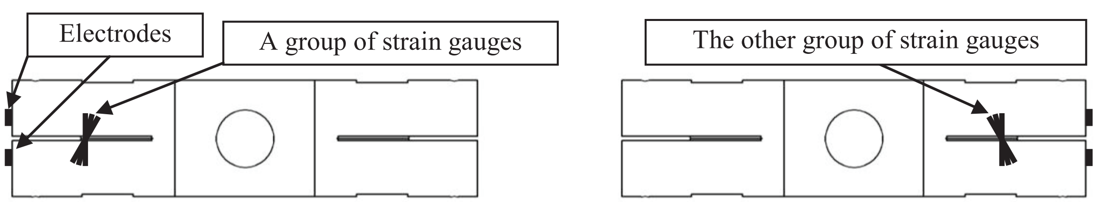

Fig. 3(a) Strain gauge pasted on the front; (b) Strain gauge pasted on the back

The crack length is measured by the AC potential method [3]. The electrodes are connected to the specimen as shown in Fig 3. As the crack grows, the electrical resistance between these two electrode points increases. The ratio of the increase in the electric potential due to the crack growth to the electric potential at the beginning of the test is correlated with the crack length. Thus, the crack length can be measured without interrupting the test. The specimen is conveniently insulated from the jig by the ceramic cylinders.

2.4 Numerical Method

As shown in Fig.4, a finite element model (FEM) of double cantilever (DC) specimens loaded in Mode II, which is with 6 nodes tetrahedron elements, refined to 10μm near the crack tip, and omitting the ceramics cylinders, central and symmetric parts, was developed, in order to investigate the ΔK_{IIth} assuming the friction distribution along the crack faces is linear. The loading was represented by the two equal forces applied to the cantilevers, while the other side was fixed.

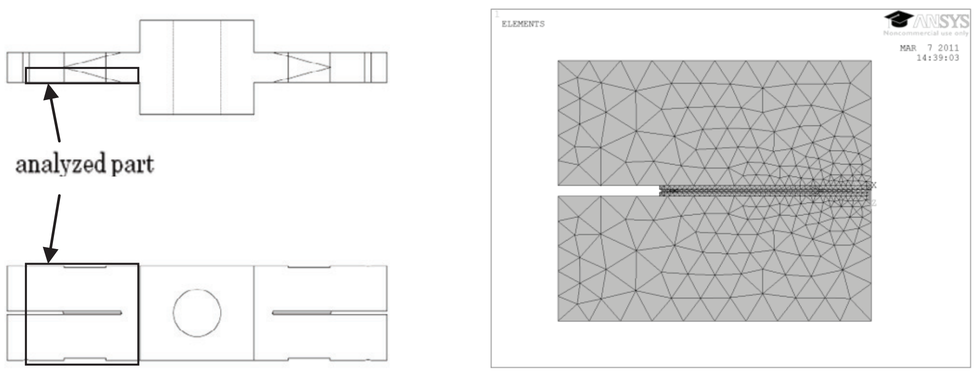

Fig. 4(a)Analyzed part of a specimen; (b) Finite element model (front view)

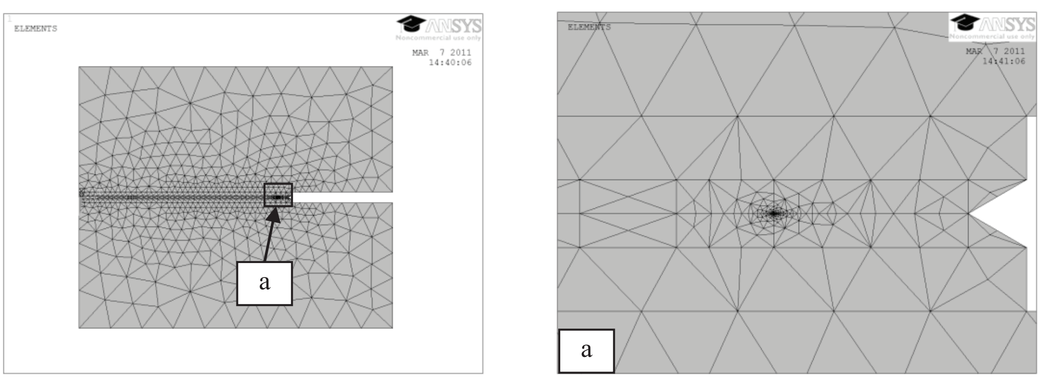

Fig. 4(c) Finite element model (sectional view); (d) Magnification of the notch tip

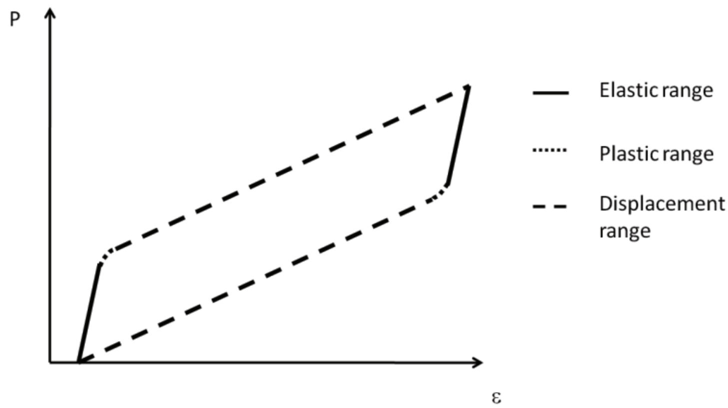

Fig. 5 Estimated load-strain curve

3. Derivation of Friction Between Crack Surfaces

The friction between the crack surfaces per unit length is equal to the elastic range of the shear stress of the crack faces. Six strain gauges were used to measure the shear strain at two points on the crack faces. Figure 5 shows the estimated load-strain curve. The elastic range of shear stress could be calculated from the elastic range of shear strain according to Hook's law. Thus, the friction between the crack surfaces could be determined by assuming that the distribution along the crack faces is linear.

4. Results and Discussion

After the test, the specimen cantilevers were separated by fracturing in liquid nitrogen in order to investigate the crack surfaces. Figure 6 shows the fracture surface of the specimen when S=0. Figure 6(b) is a magnification of Fig. 6(a). Figure 6(b) shows the trace of Mode II crack growth caused by strong abrasion in the direction of the crack growth. Figure 6(c) shows partial local branching of a crack from Mode II to Mode I growth [3]. With the friction derived from the load-curve and the crack length measured by the AC potential method, ΔK_{II} could be calculated by FEM.

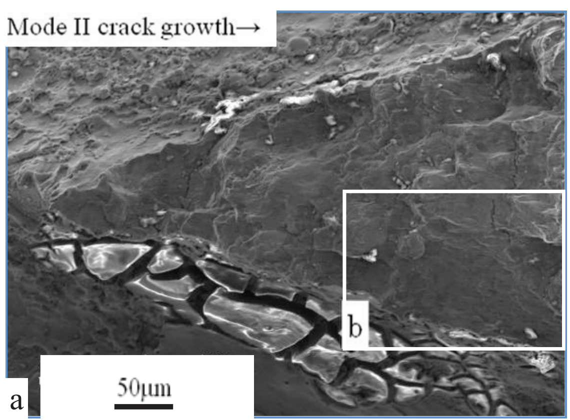

Fig. 6(a) Fracture surface of specimen

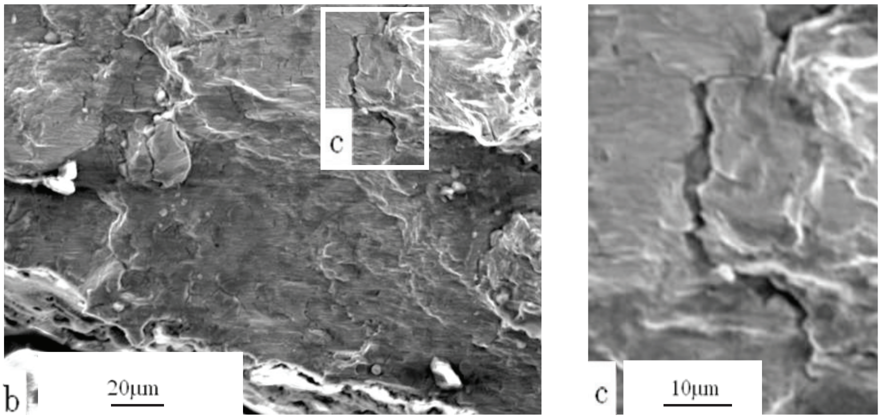

Fig. 6(b) Strongly abraded fracture surface (magnification of (a)); (c) magnification of (b)

5. Conclusions

A new experimental method to determine the Mode II fatigue crack growth using a compact specimen on a conventional fatigue testing machine is proposed. The Mode II fatigue crack growth was successfully obtained. The crack length and friction between the crack faces were supposed to be measured by the AC potential method and deduced from the load-strain curve, respectively, and the ΔK_{IIth} would then be determined. However, the value of ΔK_{IIth} has not been determined. It will to be determined by this method in a future study.

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